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Modelling of the annual mean maximum urban heat island using 2D and 3D surface parameters

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ABSTRACT: The primary aim of this study was to reveal quantitatively what effect urban structure has on the development, magnitude and spatial distribution of the annual mean maximum urban heat island using a selected representative sample area in Szeged, Hungary. In order to quantify what effect urban structure has on the development of the mean urban heat island a relatively new surface parameter (weighted volumetric compactness) was used that characterises the volume, structure and thermodynamical role of buildings. This new parameter was used in conjucntion with other established surface parameters. How the new parameter and other surface parameters can pinpoint the magnitude and structure of the heat island was investigated. The compactness of approximately 11 000 buildings in one-third of the town was determined by geoinformatical analysis. A stepwise multiple linear regression model was used to determine to what extent each parameter adds to the annual mean urban heat island intensity. According to the results presented here, the connection between compactness and the annual mean ('all weather') heat island intensity is stronger than with the sky view factor. Using this model-equation, the absolute deviations of the generated heat island (calculated for an independent 1 yr period) remained under 0.5°C throughout almost the entire investigated area of Szeged. The structure of the estimated heat island with its characteristic features showed clear similarities to the real conditions.

KEY WORDS: Urban heat island · Urban surface parameters · Weighted volumetric compactness · Geoinformatical methods · Representative sample area · Stratified sampling · Stepwise multiple linear regression model

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1. INTRODUCTION

In settlement environments such as cities, the modified surface cover has an impact on the energy and water balance of the area, which indirectly leads to the alteration of climate over the cities on a local scale. The occurrence of higher temperatures (urban heat island, UHI) is one of the main alterations (e.g. Landsberg 1981, Oke 1987, Kuttler 2005), and it has a fundamental influence on the comfort of the population of the city. In the case of mid-latitude cities (such as Szeged, Hungary) it has a double effect: negative in the summer when the nights are warmer, while in winter positive effects can be detected; the energy demand on heating is lower and the heating season is shorter. Thus, urban climate research provides important information for practical fields such as urban planning (Kuttler 2005). A modification of urban vegetation and changes in the phenological phases can be also detected due to UHI (Lakatos & Gulyás 2003).

The identification, scaling and modelling of factors which have a major impact on the development as well as the magnitude of the heat island is a complicated task partly due to the complex vertical and horizontal distribution of cities, and partly to the artificial emission of heat and pollution. The systematic collection of data is complicated and requires considerable technical investment. The intensity of the heat island is also dependent on the size of the town. Moreover, the characteristics and intensity of heat islands all over the world differ from each other presumably due to various cultural traditions in building strategies (Park 1987).

In connection with the 3D extent of a town, one of the most characteristic parameters is the sky view factor (SVF): the ratio of the radiation received (or emitted) by a planar surface to the radiation received (or emit-

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ted) by the entire hemispheric environment (Watson & Johnson 1987, Brown & Grimmond 2001). The value of the SVF has a major effect on the long-wave radiation balance as well as the rate of cooling at night, and thus on the intensity of the UHI (Oke 1981). Other parameters such as building height, vegetation height, surface area of walls, plan area fraction, frontal area index, roughness length, displacement height and mean orientation of streets (e.g. Ching et al. 2002) have also been used in urban geometric studies.

The aim of this study was to calculate the impact of the urban structure — namely the geometric structure and built-up ratio — which are mainly responsible for the annual mean magnitude and spatial distribution of the UHI, using a selected representative sample area due to the large spatial extent of the selected city (Szeged, Hungary). In addition to the SVF and the factors of built-up features, like built-up ratio, water surface ratio and building height already used to examine the UHI of Szeged (Unger et al. 2001, 2004, Bottyán & Unger 2003), the climate alteration role of building compactness was examined. This parameter (which is relatively new in UHI literature (e.g. Brown & Grimmond 2001, Ching et al. 2002, Eliasson & Svensson 2003) can characterise the volume and structure of buildings in 3 dimensions, and is of primary importance from a thermodynamic point of view. In Section 2, we first provide an overview of the research area (Szeged), then the methods used to measure temperature, and lastly, field work and geoinformatical methods. These methods are of primary importance in the exploration of the temperature distribution and different surface parameters which serve as the main basis for the creation of our model. Beyond the presentation of applied mathematical and statistical methods, we study the importance of building compactness in the modification of the UHI in order to find out the degree to which its application in a model equation (among other surface parameters) may enhance the accuracy of the description of the intensity and the spatial distribution of the heat island.

2. GEOGRAPHIC LOCATION, CLIMATIC CHARACTERISTICS, AND URBAN STRUCTURE

Szeged is located in the southern part of the Great Hungarian Plain. The surface is characterised by Holocene sediments with low relief. According to Trewartha's classification, Szeged belongs to the climatic type D.1 (continental climate with longer warm season), similar to the rest of the country (Trewartha 1966, Péczely 1979). In order to provide a more adequate description of climatic features, the regional division of Péczely (1979) is applied as well. According to his classification, the study area belongs to the warm-dry climatic region where the average temperature of the vegetation period is >15°C and the aridity index is >1.15. The annual sum of global radiation is around the average for the country (4700 MJ m^{-2}), while sunshine duration is above average (2023 h) and the percentage of clouds (57%) is below average. Wind directions were N (16%), NE (8%), E (6%), SE (11%), S (16%), SW (10%), W (11%), NW (17%), calm (5%). The annual sum of precipitation is around 550 mm, although it was well below average in recent years. Thus, the study area has high drought sensitivity.

Based on their geographical location, larger Hungarian cities can be divided into 3 groups: (1) those located in valleys, (2) those between hills or mountains and lowland, and (3) those on lowland. From the viewpoint of urban climate development, the study of the first 2 groups is very complicated, as it is difficult to separate the effects of topography and possible human impact. Being part of the third category, Szeged has a topography which is favourable for urban climatology research so the results of systematic measurements and analysis can be applied as a basis of general conclusions.

While the administrative area of Szeged is 281 km^2, the inner city is only around 30 km^2, and the densely built-up areas are located inside a circular dike. The avenue-boulevard structure of the town was built parallel to the axis of the river Tisza. The following main land-use types can be distinguished (Fig. 1):

- relatively densely built-up downtown, where mainly narrow streets are closed from both sides by high buildings;
- blockhouse areas where high uniform buildings are located relatively far from each other, with extensive open green areas in between;
- industrial and warehouse districts, which are characterised by extensive halls of low heights and large horizontal extension mainly with solid cover in between the buildings;
- detached housing district, with buildings of small area — one or 2-storied houses — with large open areas of garden vegetation with trees;
- parks and the gallery forest located at the banks of the River Tisza and in the outskirts which are usually covered by vegetation; the buildings and the solid cover represent a much lower percentage of the area.

3. METHODS OF FIELD WORK AND GEOINFORMATICAL MEASUREMENTS

3.1. Study area and collection of temperature data

Research was mainly concentrated on the inner parts of the town. In order to systematise the data collected, the study area was divided into 500 × 500 m grid cells

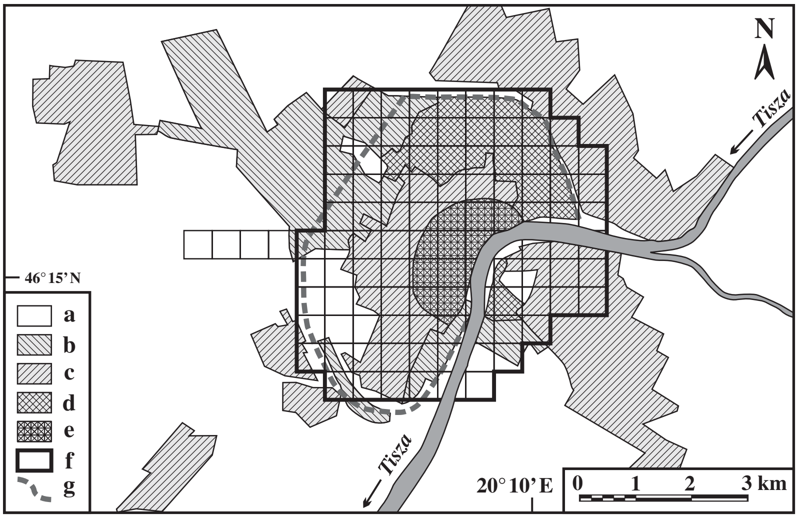

Fig. 1. Generalized built-up types of Szeged: a, agricultural and open area; b, warehouses and industrial area; c, 1–2 storey detached houses; d, 5–11 storey blockhouses; e, city core with 3–5 storey buildings (the investigated area and the grid network); f, border of the investigated area; g, circular dike

(Fig. 1). A similar grid size (0.25 km^2) was applied in other urban climate projects (e.g. Park 1986), and similar examples can be found in e.g. Long et al. (2003) and Lindberg et al. (2003). The study area consisted of 103 cells, covering the downtown area as well as the suburbs. The 4 remaining cells extended towards the west were applied as a reference area to which temperature data could be compared.

Data necessary for the analysis of the maximum UHI intensity were collected in a full (107 cell) measurement network (Fig. 1), with the help of cars equipped with temperature sensors following given routes, in periods between March 1999 and February 2000 as well as between April 2002 and March 2003. The use of such 'mobile' measurements is widespread in the study of urban climate (e.g. Oke & Fuggle 1972, Moreno-Garcia 1994, Ripley et al. 1996, Klysik & Fortuniak 1999, Santos et al. 2003).

In the study area, mobile measurements were carried out once a week, 48 times in total in 1999/2000, and once every 10 d (in total 35 times) in 2002/2003. From these observations a representative amount of sample data was gathered to study the development of the UHI. The 3 h (approx.) measurements taken covered all weather conditions except for rain. On the basis of previous studies, data collection was carried out in such a way that the observations took place around the expected maximum development of the UHI, i.e. 4 h after sunset; this time is based not only on other research (e.g. Oke 1981), but also on earlier measurements in Szeged carried out in 1998 and 1999 (Boruzs & Nagy 1999). After averaging the measurement values by grid cells, time adjustments to the reference time (4 h after sunset) were applied assuming linear air temperature change with time (which was monitored using the continuous records of the automatic weather station at the University of Szeged). However, due to the different cooling gradients, this temperature change with time is only approximately valid in the suburbs (Oke & Maxwell 1975).

Due to the size of the study area as well as the length of the routes used to make measurements, the area had to be divided into 2 sectors. Routes had to be determined so that all cells could be reached at least once (i.e. travel to the cell and back to starting point within a certain period of time) (Fig. 1). Temperatures were measured using an automatic radiation-shielded sensor connected to a digital data logger that provided data every 10 s. In order to diminish the thermic effect of the car, the sensor was attached to a bar which extended 0.6 m in front of the car and was 1.45 m above the ground. To ensure efficient ventilation and density of data, the speed of the car was 20 to 30 km h^{-1}. Thus, data gathered from every 55 to 83 m travelled was available. Measurements were taken after the peak traffic hours, so stops due to red lights or other barriers were seldom: data recorded when the car was stopped was later deleted from the database.

In our case the UHI intensity (ΔT) can be characterised as follows:

$$\Delta T = T_{\text{cell}} - T_{\text{cell(W)}} \quad (1)$$

where T_{cell} is the temperature of the actual town cell; $T_{\text{cell(W)}}$ is the temperature of the westernmost cell of countryside location (Fig. 1). This cell consists of agricultural land (mainly non-irrigated wheat, sunflower and maize fields) representative of the rural surroundings. The ΔT values of the cells from the 35 individual measurements have a range of 0–7° C.

3.2. Determination of urban surface parameters

3.2.1. Built-up ratio, water surface and sky view factor

The determination of the built-up ratio (covered surfaces: streets, roofs, parking places, etc.) was based on the analysis of SPOT XS satellite images from the summer of 1992. The resolution of the images is 20 m, which makes it possible to take the small-scale areal characteristics of the town into account. The basis of analysis was the calculation of the Normalised Difference Vegetation Index (NDVI) by geoinformatical systems based upon both raster and vector data. Using this index, it was possible to determine the ratios of the built-up surfaces (B) and water surfaces (W) belonging to the cells (e.g. Unger et al. 2000).

Numerous solutions are known for the calculation of the SVF parameter: application of theodolite in angular measurements (e.g. Johnson 1985), analysis of photos taken by fish-eye lens camera (e.g. Oke 1981, Holmer 1992), the application of the software analysing the 3D geometry of the surface (e.g. Souza et al. 2003, 2004), and use of GPS receivers (Chapman et al. 2002, Chapman & Thornes 2004). We determined the approximate values of the SVF using a theodolite. We measured the angles of elevation at each 100 m along the route using the highest points of the buildings located on both sides of streets as reference points (Bottyán & Unger 2003).

3.2.2. Parameters of compactness

In recent urban geometry studies, much more emphasis has been placed on the size and shape of buildings in a given area. In addition, numerous efforts have been made to find the most efficient parameter to describe all this information. One of these parameters is the so-called compactness, which, according to the definition of Long et al. (2003), is the ratio between the perimeter of the building and the perimeter of a circle of a similar area. This parameter is important primarily due to its aerodynamics. This value describes a 2D slice of urban geometry; however, the impact of the vertical structure on the physical conditions of the air is also significant. By applying statistical methods, it is possible to determine the connection between the UHI and the new 3D parameters (e.g. the building mass, BM) created by geoinformatical evaluation (Santos et al. 2003). In the case of the BM parameter, the authors described the building — regardless of its surface — by its volume, and the weight calculated from the volume, which is related to the heat-storing capacity of the given building.

Therefore, in order to find a relationship between the surface geometry and the UHI, we must find a parameter more efficient than the previous one. This parameter has to fulfil the following requirements:

- it should describe the surface of buildings based on their heat emission to and absorption capacity relative to the ambient air;
- it should provide information not only along the measurement route, but also for the whole research area; i.e. the entire urban surface is described;
- it should include the volume (or weight) and thus, also describe heat storage values of buildings.

By applying geoinformatical methods (Section 3.3), it is possible to determine the height of walls (H), the area (A) and the perimeter (P) of buildings. From these parameters the surface (S) is also calculated. Nevertheless, we must consider the fact that the plan areas of buildings are not counted directly as an active surface from the viewpoint of the air mass nearby. Therefore, while calculating the active surface of a building (S_b), we do not take the plan area of a building into account:

$$S_b = P \cdot H + A \qquad (2)$$

In general, a given body cools more slowly if its surface belonging to a given volume is smaller. Similarly, a body can store more heat if the volume belonging to a surface is larger. Therefore, it seems more practical to take the volume/surface ratio of bodies into account when determining a new parameter. However, this is only partly true because the cooling rate is dictated by the surface geometry. Even with a very large surface area, cooling will be impeded if the long-wave radiation cannot escape but is trapped by street canyons. Similarly, a structure with very incised walls may have a larger surface area, but not necessarily all of it will be fully exposed to incoming solar radiation and therefore be radiatively active.

In this study we use the most compact building form, the cube, as it corresponds broadly to a house-like shape and, out of all prismatic buildings of a given volume, the surface of the cube is the smallest (Fig. 2). As a result, the surface geometry of Szeged is compared not only to the non-built-up rural surface, but also to an ideal settlement that consists of homogeneous, cube-shaped buildings, and contains exactly the same number and volume of buildings as the real settlement.

We also calculated, with an approximate value, the volume of a given building, omitting the smaller parts of the walls and the roofs. This geometrical simplification is possible due to the fact that many flat-roofed buildings exist in the area (e.g. blockhouses as well as industrial buildings etc.). Moreover, the description of the volume of more complicated bodies — which is the case for many thousands of buildings — would be virtually impossible with a single formula. The simplified volume of a building (V_b) is calculated in the following way:

$$V_b = A \cdot H \qquad (3)$$

Consequently, for a given building, the data for the volume (V_b) and surface (S_b) parameters are available. On the basis of Eq. (4) it is possible to calculate the side length (a) and thus the active surface (S_c) of a cube of similar volume (V_c):

$$V_b = V_c = a^3, \qquad S_c = 5 \cdot a^2 \qquad (4)$$

Dividing the building surface (S_b) by the cube surface (S_c) results in a dimensionless ratio >1, which,

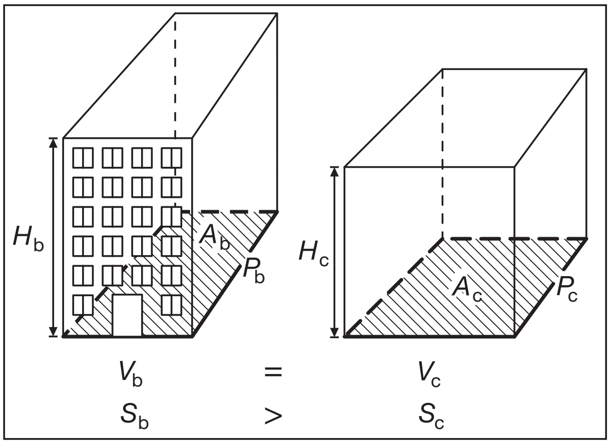

Fig. 2. Comparison of a city's building characteristics with that of a cube; A_b, A_c, P_b, P_c, H_b, H_c, V_b, V_c, S_b and S_c mark the area, perimeter, height, volume and surface of the building and the cube, respectively

from a geometrical perspective, means the deviation of a given body from the cube. This ratio is called compactness (C). Since the above-mentioned parameters (ΔT, B, W, SVF) were determined for cells, it is possible to apply this method to the new parameter as well. Its cell mean is called average compactness (C_m):

$$C = \frac{S_b}{S_c}, \quad C_m = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{5}$$

However, the number and size of buildings are very different in each cell, so the value of C_m might be inaccurate for defining this physical characteristic. As a result, the compactness value (C) of a house should be multiplied by the volume (V_b) of the house. Thus, compactness is weighted by the value of the volume, and then summarized values are calculated to all the buildings of the cell (replaced in Eq. 5). The new index (C_v) is the weighted volumetric compactness (m^3):

$$C_v = \sum_{i=1}^{n}(C_i \cdot V_{bi}) = \sum_{i=1}^{n}\left(\frac{S_{bi}}{S_{ci}} \cdot V_{bi}\right) \tag{6}$$

3.3. Geoinformatical methods and application

Geoinformatics is applicable when handling large-sized databases and maps. Using this method the analysis, measurement and presentation of data are all possible. A special branch of geoinformatics is digital photogrammetry, which — as is implied to the definition — is the science of image creation, handling and analysis without physical contact with the actual object. While photos are taken by digital cameras or an analogue information holder, traditional film has to be digitised by scanning. During the photogrammetrical processing, the spatial position of the object at the time of shooting (exterior orientation) is reconstructed. After orientation it is possible to measure and map spatial extensions using photos taken from 2 positions.

3.3.1. Analysis

The Digital Elevation Model (DEM) is a general spatial model which represents bare surface without any landmarks. In the case of Szeged variations in elevation are small (75.5–83 m a.s.l.), so using a DEM enabled us to increase accuracy (as the DEM determines the accuracy of the orthophoto). After the digitisation of the 1:10 000 scale maps (geodesic-topographic maps of the Unified National Mapping System [Hungarian acronym: EOTR], nos. 27–323, 27–332, 27–341, 27–342, 27–343), contour lines were vectorised in ERDAS IMAGINE (in Arc/Info format), and then with the help of the Create Surface application we produced the elevation model of the research area. Later this DEM was used for the preparation of orthophotos and visualisation of the model in VirtualGIS.

Geoinformatics, and in particular digital photogrammetry, was used to reconstruct the spatial position of buildings in Szeged. Aerial photos (30 in total, scale 1:11 000) were taken of Szeged on November 13, 1992, from 11:45 to 12:15 h at a flight altitude of 1760 m. The negatives were scanned in 14 micron (~1800 dpi) resolution. The formats of aerial photos were TIFF, BMP, PCX, and LAN. For further use it is necessary to transform the TIFF format into the IMG format, which is the ERDAS IMAGINE format . The basis of orthocorrection is the DEM. The process involves the creation of a Block File, measurement of the adjusting points, aerial triangulation, as well as the creation and quality-control of orthophotos.

We defined a building area limit of 15 m^2, as the heat absorption and heat emission of structures smaller than this size are negligible. Moreover, such structures are not always visible on the aerial photos of the area.

After an analysis of a suburban and a downtown cell, it became clear that in the suburban cell the number of buildings with an area of <15 m^2 comprised more than one-third (39.4 %) of all the buildings in the cell, but covered only 4.1 % of the whole built-up area of the cell. In the downtown cell, less than half of the buildings (46.7 %) were smaller than the limit, but they covered only 1.7 % of the whole building area of the entire cell.

In order to make orientation easier we superimposed the building plan areas on the IMG format orthophotos. Both vector and raster format data were kept in the Unified National Projection (in Hungarian abbreviated EOV) and, thus, they overlapped each other exactly (layer structure).

3.3.2. Measurement and visualisation

3D measurements were carried out in the ERDAS IMAGINE Stereo Analyst module using the anaglyph method. Three parameters per building were measured: street level, eaves level and roof level. We also took note of roof types.

One way to achieve 3D visualisation in ERDAS IMAGINE is by using Image Drape. With the help of Image Drape, a picture can be presented applying the relevant DEM so that it entirely overlaps the topographic model. Viewpoint and other parameters can be freely changed. When adequate elevation data is chosen, it is possible to create a simplified 3D image of the buildings. Fig. 3 shows structural-morphological differences within the town. The picture provides a view of a part of Szeged.

Fig. 3. Bird's-eye view generated by VirtualGIS of a part of Szeged

3.3.3. Update and accuracy of building parameters

In the aerial photos of 1992 large shopping centres did not exist, although they were already included in the layout-database we used. Since these giant buildings, together with the extensive parking areas attached, can significantly influence the thermic conditions of their environments, a data update including these structures was of primary importance. In the present study, the aerial photos of 5 August 2003 were used. As a result, we gathered a dataset of surface parameters that is strongly connected in time to the periods of temperature measurements.

Theodolite measurements were also carried out in the cells located at the edge of the study area. Here, the error due to aerial triangulation could be expected to be the greatest; the mean ratio of the differences in value compared to the total heights of the buildings was around 5%, while the average deviation (based on an element number of almost 100) was only 58 cm.

4. MATHEMATICAL METHODS

4.1. Selection of the representative sample area

The broader aim of the research was to determine the geometrical-morphometrical parameters for describing the whole area, and to study their impact on the UHI. A geometric survey of the whole town would involve enormous effort and time due to the great number of buildings (22000) present. Therefore, we limited our sampling to one-third of the research area, which contained 35 cells.

4.1.1. Stratified sampling

Stratified sampling is a sampling design in which prior information about the population is used to determine groups (called strata) that are sampled independently. Each possible sampling unit or population member belongs to exactly 1 stratum. When the strata are constructed to be relatively homogeneous with respect to the variable being estimated, a stratified sampling design can produce estimates of overall population parameters (e.g. mean, proportion) with greater precision than estimates obtained from simple random sampling. The variable providing the information used to establish the strata (that is the so-called 'auxiliary variable') was the built-up ratio.

The fact that an increase in precision depends on the strength of the correlation between the auxiliary variable and the outcome variable to be estimated may theoretically be a restricting factor. If there is no significant correlation between the auxiliary variable and the one being estimated, the precision of the final estimation can be significantly decreased.

Cochran (1963) offers some guidelines on how to optimally assign strata when the auxiliary variable is continuous. If there is a particular interest in estimating the overall mean for the population, he suggests defining no more than 6 strata and using a procedure attributed to Dalenius & Hodges (1959) to determine the optimal cutoff values for each of the strata based on the distribution of the auxiliary variable for the population.

In this study, 6 strata were defined and the number of elements in samples by strata were determined by applying a method devised by Dalenius & Hodges (1959). Table 1 shows the final result of defining the 6 strata.

4.1.2. Selection based on spatial distribution

When selecting the appropriate cells from the strata, the priority was to find the most balanced distributions. Moreover, it was also important to include some specific parts of the town with significant temperature anomalies where surface conditions suddenly change.

In the course of the selection we had several adequate alternatives, but kept only those where the mean heat island field — interpolated from the data of 35 cells — was the closest to the mean field constructed from values of 103 cells, both from the point of view of structure and intensity. As a result of this process, cells inthe chosen sample area have relatively scattered locations within the whole research area (Fig. 4). In those places where the chosen cells were located near each other, the horizontal temperature gradient was high at the time of the development of the UHI.

4.2. Stepwise multiple linear regression model

Our purpose here is to determine the relationship between static parameters describing the town and the mean maximum heat island intensity (ΔT). When constructing the statistical model of the mean spatial temperature distribution (ΔT), for the period from April 2002 to March 2003, we used the following urban surface parameters (referring to cells): built-up ratio (B), water surface ratio (W), mean sky view factor (SVF), mean compactness (C_m) and weighted volumetric compactness (C_v).

In previous studies (Bottyán & Unger 2003, Bottyán et al. 2003) the connection between the urban surface parameters (B, W, SVF, H = building height) and the mean UHI intensity is explained by a linear function. Thus, when the present model was constructed, a linear approach was also applied.

Table 1. Number of cells in each stratum, and in each sample

Label of stratum	In stratum	In sample
1	11	4
2	14	5
3	18	6
4	20	7
5	22	7
6	18	6
Total	103	35

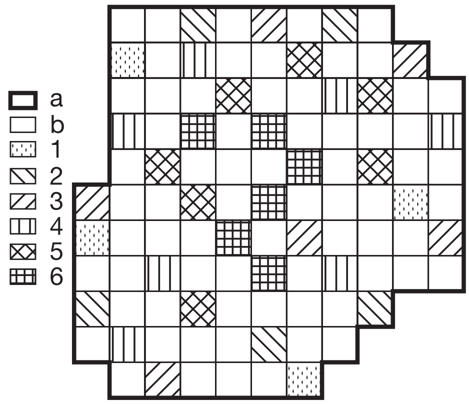

Fig. 4. Distribution of the cells sampled in Szeged; a: border of the investigated area, b: cells not included in the sample, 1–6: cells selected from the given strata

We presumed that all 5 parameters have a significant impact on the spatial distribution of ΔT. First, all factors were included in the database (as predictors). We selected the statistically acceptable predictors, later applied in the model, using a stepwise linear regression method. In the process we applied the SPSS for Windows 9 software. Limits of predictors were entered or removed from the model depending on the significance of the F-value of 0.05 and 0.1, respectively.

5. RESULTS

5.1. Representativity

It would not be appropriate to study the spatial representativity of the sample area by using the spatial distribution of the interpolated values of the built-up ratio, since none of the interpolation methods are suitable for the spatial extension of such a rhapsodically changing parameter.

Both in previous research (e.g. Unger et al. 2000) and in our present study (see Section 5.2) the strongest relationship occurs between the heat island and the built-up ratio. In the process of stratified sampling we used this parameter as an auxiliary variable. As expected from the applied selection methods, when comparing the structure of the ΔT constructed from data taken from the whole area to the one constructed from 35 cells, it appears that the smaller version of the heat island field is simpler and the isotherms are more settled and less detailed, but its main characteristics are basically similar to the field based on the complete database (Fig. 5a,b).

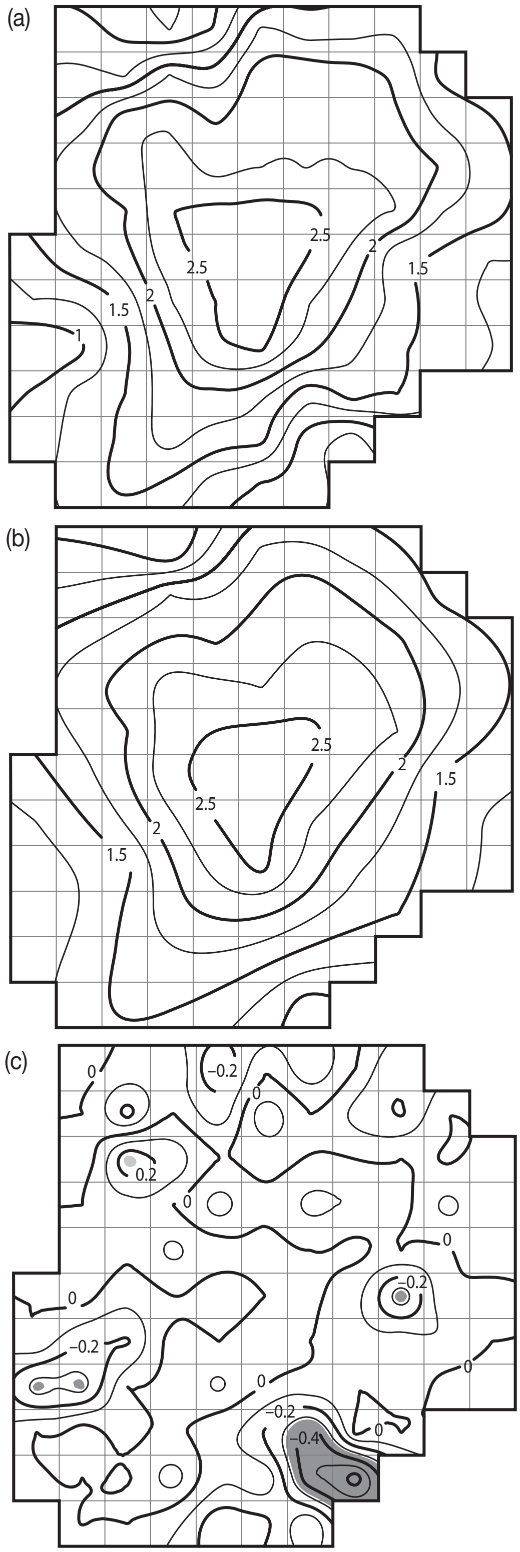

Fig. 5. Spatial distribution of the annual mean maximum urban heat island (UHI) intensity based on (a) the complete database and (b) data from the 35 cells selected (April 2002–March 2003); (c) difference between (a) and (b). Upper (0.25°C) and lower (–0.32°C) confidence limits shown by light and dark grey shading, respectively

As for the map showing differences (Fig. 5c), only small-scale alterations occurred and, ¾ of the area, this difference was <0.1°C. The mean error of the selection of cells was –0.035°C, while the standard deviation was 0.11°C. In order to identify the values significantly different from the mean deviation (i.e. where selection of cells was not appropriate), the confidence limit belonging to the database had to be calculated. The most significant positive deviations occurred in <0.1% of the area, while negative deviations occured in <3% of the area.

The small values of deviation prove that the temperature fields of the sample area and the whole area of Szeged are similar and therefore the selection process was successful. Nevertheless, it is still important to take into account the afore-mentioned deviations because they present the maximum accuracy of the modelled heat island field (see Section 5.3).

5.2. Relationships between urban parameters and the UHI

As a first step, the relationships between the annual mean maximum UHI intensity and values of surface parameters were analysed and compared in pairs using data from the 35 cells. During this process we identified the linear regression equation referring to the closeness of the stochastic realtionship between each parameter and the ΔT as well as the values of the coefficient of determination (R^2) and the standard deviation (σ_R) around the regression line.

The null hypothesis, namely that there is no real relationship between 2 chosen parameters, can occur only when the value of the coefficient of determination is large enough. The confidence interval of the null hypothesis (35 cells at the 5% significance level), was $R^2 > 0.1089$ (Péczely 1979).

The hypothesis, namely that C_v is an essential factor in UHI development and therefore there is a strong stochastic relationship between them, was proved in the correlation examination. Based on the regression equation, the increase in C_v values results in higher urban–rural temperature difference (Table 2).

Based on our calculations, the closest relationship was detected between the parameters B and ΔT (see e.g. Bottyán & Unger 2003). This is not a surprising result as the main reason for choosing this sample area was exactly this surface parameter (B). The relationship between the SVF and the ΔT is statistically significant, though lower in comparsion with the results of other similar research (e.g. Oke 1981). This can be explained by the conditions of these investigations which were carried out under 'ideal' weather conditions. The coefficient of determination belonging

Table 2. Relationships between surface parameters and urban heat island (UHI) intensity (ΔT). B: built-up ratio; W: water surface ratio; SVF: mean sky view factor; C_m: mean compactness; C_v: weighted volumetric compactness

	Linear regression	R^2	σ_R (°C)
B	$\Delta T = 0.0165 \cdot B + 0.8005$	0.6619	0.293
W	$\Delta T = -0.0019 \cdot W + 1.7965$	0.0332	0.504
SVF	$\Delta T = -3.4219 \cdot \text{SVF} + 4.8782$	0.3584	0.404
C_m	$\Delta T = 0.0363 \cdot C_m + 0.9351$	0.2976	0.423
C_v	$\Delta T = 2 \cdot 10^{-7} \cdot C_v + 1.4827$	0.5243	0.348

to the C_v parameter is close to the value of the built-up ratio (Table 2). On the basis of these preliminary results we can conclude that in the case of investigation of the annual mean UHI intensity structure, the C_v parameter carries significantly more information in the explanation of the ΔT pattern than does, for example, SVF.

5.3. Stepwise multiple linear regression

With the application of multiple linear regressions, 3 out of the 5 original predictors were statistically acceptable for the estimation of the UHI intensity (Table 3). The importance of these 3 parameters in the development of temperature excess was almost 80% ($R^2 = 0.786$, $p < 0.01$). This fact clearly shows that by entering the afore-mentioned parameters, the increase in the value of the explained variation (R^2) decreases stepwise. Entering the C_v parameter resulted a 9.2% increase (ΔR^2) in the explanation, then predictor W enlarged this value by 3.2%. The application of the 4th and 5th parameters (SVF, C_m) does not provide more information to the model in practice, and thus, they can be excluded from the model. In the case of the SVF, this fact is surprising, because according to some earlier studies (Bottyán & Unger 2003, Unger et al. 2004) a strong correlation was detected between the SVF and ΔT. This can be explained by the likelihood that it is in multi-collinearity with the C_v, as both parameters refer to the vertical structure of the town, and therefore only the stronger predictor appears in the model.

Table 3. Significance levels and correlation values of the stepwise linear regression between the mean maximum UHI (April 2002–March 2003) and the surface parameters (n = 35). See Table 2 for definition of parameters

Parameter entered	Multiple R^2	ΔR^2 level	p
B	0.662	0.000	<0.001
B, C_v	0.754	0.092	<0.001
B, C_v, W	0.786	0.031	<0.001

Afterwards, on the basis of the sample data, estimation is given for the value of regression model coefficients (Table 4). This is important because in the case of known coefficients, a model equation can be described. Using this equation, it is possible to estimate the heat island intensity of the cells and thus spatial structures can be constructed. It appears in Table 4 that the estimation of regression coefficients is especially good, as significance values are above 95% in all cases. What is more, this value is smaller than 99% only in the case of the W parameter. The model equation is calculated as follows:

$$\Delta T = 1.332 \cdot 10^{-2} \cdot B + 1.045 \cdot 10^{-7} \cdot C_v + 1.082 \cdot 10^{-2} \cdot W + 0.809 \qquad (7)$$

Using Eq. (7), it is possible to estimate the value of any of the 35 cells. In this statistical model, special attention must be paid to the problem of extensibility, namely, that the model can be applied only with parameters between the minimum and maximum values applied at the beginning. In this case, however, the above-mentioned fact does not have any determining effects. Nevertheless, were the model to be applied to another town, the predictors used would need to be within the adequate intervals. Minimum and maximum values of predictors are given in Table 5.

With the help of the Kriging interpolation method (linear variogramm model application), the calculated ΔT values provided a basis for the spatial extension of the above-mentioned values (B, C_v, W). Using this extension, it is possible to determine the spatial distribution of the UHI intensity and, thus, the whole mean heat island can be explored, practically without any temperature measurements (Fig. 6a). Naturally, it is useful to test model and, thus, to compare the ΔT field calculated by the model equation to an independent database collected in another period.

5.4. Spatial extension and model verification

We studied the accuracy of the heat island field estimated by the model equation (Fig. 6a) in a number of

Table 4. Coefficients, standard deviation (SD) and significance level of the stepwise regression model

Parameter	Coefficient	SD	p
B	1.332×10^{-2}	0.002	<0.001
C_v	1.045×10^{-7}	0.000	0.002
W	1.082×10^{-2}	0.005	0.041
Constant	0.809	0.123	<0.001

Table 5. Minimum and maximum values of predictors and predictand applied in the stepwise regression model, namely the intervals of model-application by cells (in the case of ΔT the values are annual means of cells)

Parameter	Lower value	Upper value
B (%)	3.24	93.8
C_v (m^3)	1849.54	7 411 700.05
W (%)	0	40.36
ΔT (°C)	0.74	2.72

steps. The temperature measurements, which were made between March 1999 and February 2000, were taken as independent reference data referring to the calculated heat island intensity values of the town.

The first step was to calculate the difference between ΔT values estimated by the model equation and real intensity data interpolated from the values of the 35 cell sample area (Fig. 6b). On the basis of these differences we can conclude that the model overestimates real values: the mean deviation is 0.22°C. The absolute deviation, which is <0.1°C, extends to more than one-third of the whole study area.

With the help of the determined bounds of the confidence interval of the data set, we can recognise the areas with especially striking errors. In these areas the estimation of the model significantly differs from the value of the mean error. Greater negative errors appeared in <1% of the study area, while positive errors occurred in around 3% of the study area.

The map of differences between the modelled UHI field and the mean maximum UHI (Fig. 6c) shows those areas where the result of modelling was not entirely acceptable. These deviations can be explained by the fact that the model does not take the values of neighbouring cells into account. This is the equalising effect, which indirectly occurs in the given cell while creating the measured UHI intensity. With greater positive deviations the problem is that the estimation gives the same values to the cells of suburbs as to the densely built-up downtown cells. There was only 1 cell with a negative deviation: this was presumably caused by the effect of the River Tisza and, thus, the values of surface parameters decreased. Since temperature was not able to follow this sudden change, the real temperature must have been higher than the estimated one.

Afterwards we calculated differences between the ΔT values estimated by the model equation and the real intensity values of the entire study area of 103 cells (Fig. 6c). On the basis of these differences, the mean error of the model and the extension was 0.24°C, which is not much more than the error of the model in itself. Most of the errors are probably attributable to the selection procedure for the cells of the sample area.

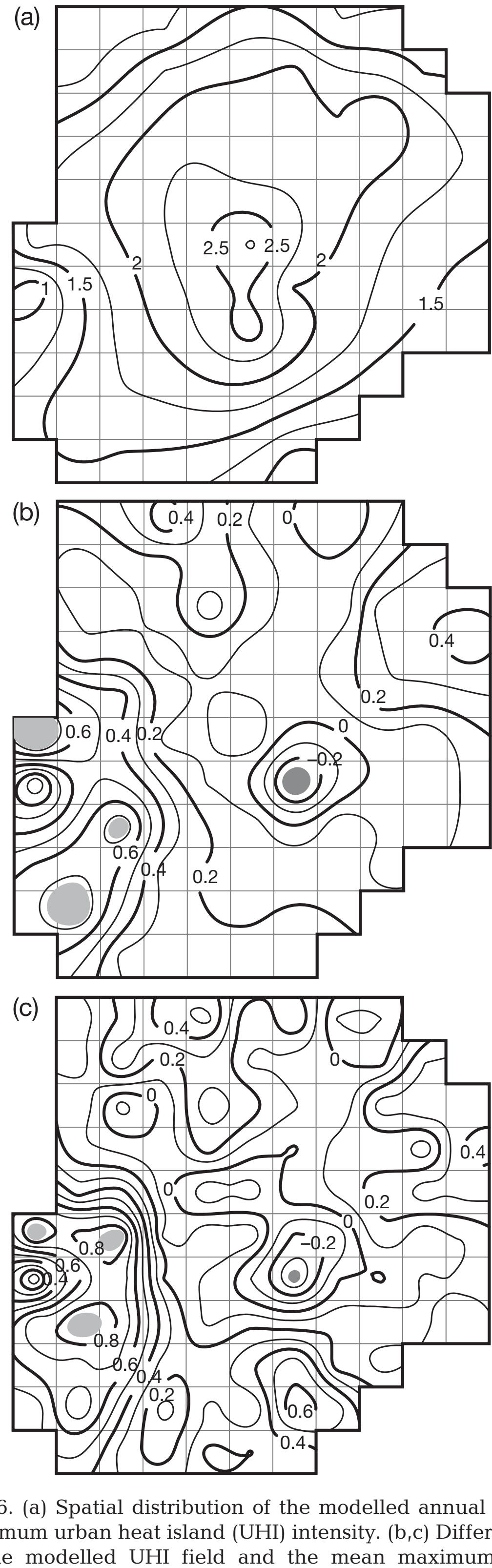

Fig. 6. (a) Spatial distribution of the modelled annual mean maximum urban heat island (UHI) intensity. (b,c) Differences in the modelled UHI field and the mean maximum UHI (March 1999 – February 2000) based on cell data from (b) the sample area or (c) the entire study area (°C). Light grey shading shows upper (0.72°C, 0.84°C) and dark grey shading shows lower (–0.28°C, –0.36°C) confidence limits

Taking all these factors into account, the values estimated by the model are closely related to the independent temperature values taken in the city. In the analysis of deviations, we have to consider that on the basis of data taken from the sample area a pattern of the whole heat island can be provided with few errors. The spatial distribution of larger differences points to the fact that by possessing the database of the whole area, a more adequate model might be created if we can also apply, in model building, the characteristics of the neighbourhood around a given cell.

6. CONCLUSIONS

Our aim was to create a model in order to estimate the intensity and spatial distribution of the mean maximum heat island with the help of urban-surface parameters as well as mathematical-statistical methods. In the course of this work we applied some new parameters that describe urban geometry in 3 dimensions. Of these parameters, the application of weighted volumetric compactness as a predictor appeared to be successful in the model.

Geoinformatical application is a reliable and time-saving method. With this application a large dataset of the examined parameters can be generated: it possible to gather 3D data from a few aerial photos, and then generate new ones from these data. Thus, during the analysis of measurement results, very useful, and later, applicable transitionary data (e.g. building plan area, height, volume) were gathered.

As far as we know, such a detailed measurement and analysis of surface geometry for urban climate research has not been carried out in Europe. In the course of our measurements it was possible to quantify the spatial data of 11 000 buildings with great accuracy and, thus, a more complex analysis of the connection between urban geometry and the heat island was gained. The volumetric compactness, similar to the predictors describing the urban surface, strongly correlates with the average ('all weather') UHI intensity; in addition, it became clear that in this case it provided an even stronger relationship than the SVF.

With the application of the stepwise multiple linear regression model we could determine coefficients showing to what extent each parameter takes part in the creation of the annual mean UHI intensity. Using this model equation, the absolute deviations of the generated UHI (calculated for an independent 1 yr period) remained <0.5°C for almost the entire investigated area of the town, which is an appropriate result. The spatial features of the calculated UHI also showed clear similarities to the real conditions.

In this study, one aspect of the current results in the urban climatology research of Szeged is discussed in detail. The next step in our project is to finish the 3D urban geometry survey, which should help us provide a more exact model of the UHI. Moreover, in the model it is possible to take the effects of the neighbouring cells into consideration. Our further aim is to apply the model to other towns with conditions which are favourable for urban climate research (e.g. Debrecen, Hungary). Thus, it will be possible to develop a general model which should enable us to calculate the spatial distribution of mean maximum UHI practically without any temperature measurements, merely by the application of urban surface parameters. These types of data are available for more and more settlements. Thus, we think that the results of our present investigation can be applied to cities where the geographic conditions (e.g. climatic, geomorphological and topographical conditions), size, population, building traditions are similar to our investigated settlement. This model could be applied in a wider region of Central and Eastern Europe: the Hungarian, Romanian, Serbian, Ukrainian, German, Polish and some Russian cities meeting the above-mentioned conditions. Therefore, by estimating the spatial distribution of UHI intensity, which has a significant influence on energy consumption and human comfort, such a simple model can help in urban planning.

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